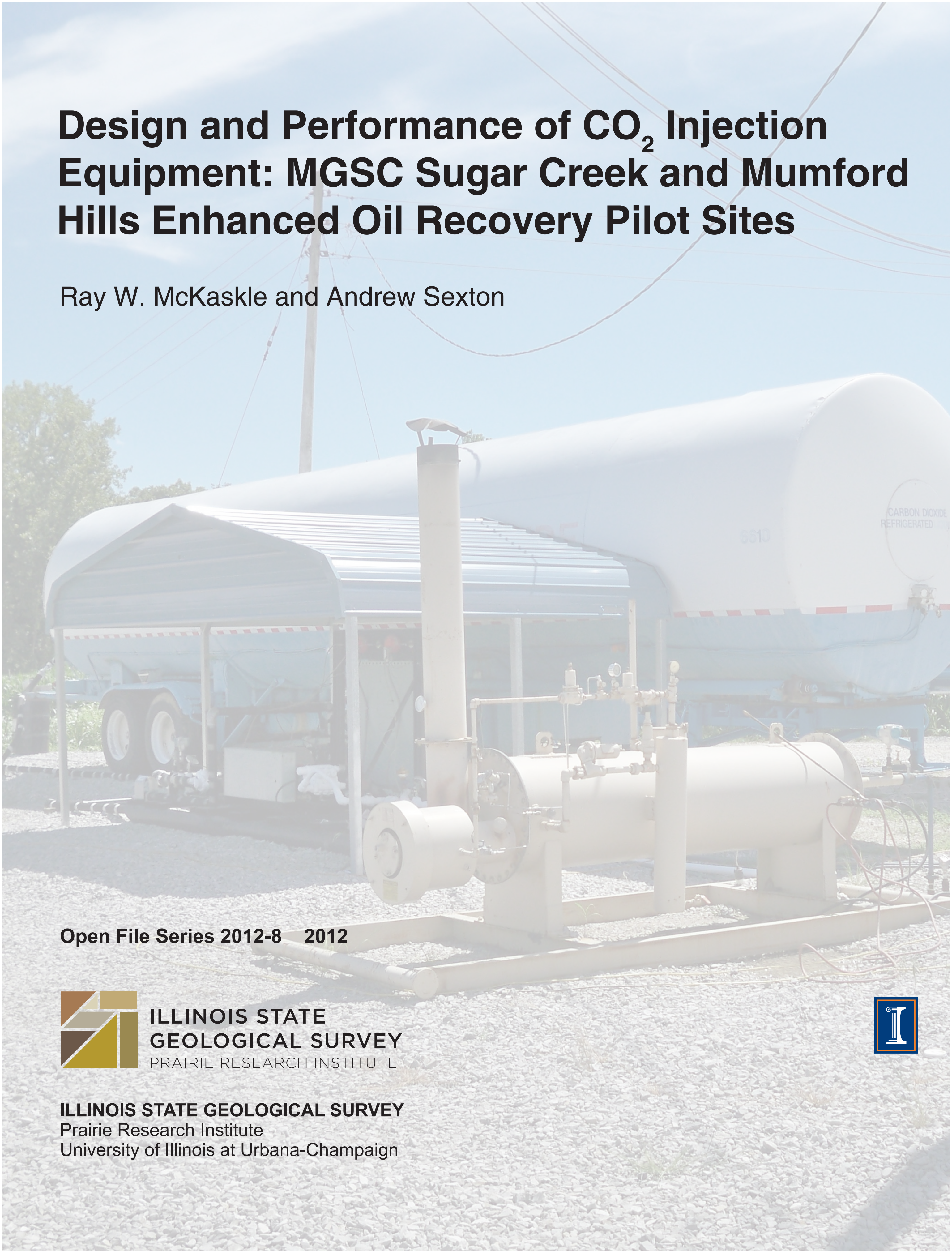

Design and Performance of CO_2 Injection Equipment: MGSC Sugar Creek and Mumford Hills Enhanced Oil Recovery Pilot Sites

Ray W. McKaskle and Andrew Sexton

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Midwest Geological Sequestration Consortium

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Gallagher Drilling Inc. designed most of the equipment used for the Mumford Hills and Sugar Creek tests. Trimeric Corporation designed the automated injection pressure control systems used for these tests and provided field support to commission the automated injection pressure control systems at both sites. Gallagher Drilling Inc. personnel operated all the equipment during the Mumford Hills and Sugar Creek tests. Trimeric Corporation appreciated the opportunity to work on this project with the ISGS. We enjoyed working with Scott Frailey and the rest of the team at ISGS. It was interesting for us to see the way Scott worked to fit so many different aspects of technical work together on the Midwest Geological Sequestration Consortium Phase II injection tests. The CO_2 storage and injection equipment is just one of many parts of the whole that were carefully coordinated to obtain the injection test results for this project. Mike Gallagher of Gallagher Drilling Inc. was generous with his time in support of the development of this report. Mike and the team at Gallagher Drilling Inc. used an economical, yet flexible design on the equipment they provided for this project, and the Trimeric team learned a great deal from working with them.

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ABSTRACT

This report describes the design and performance of the surface equipment used for CO_2 storage and injection during the Midwest Geological Sequestration Constortium (MGSC) Validation Phase (Phase II) enhanced oil recovery (EOR) pilot test at the Mumford Hills, Indiana, test site (EOR II) from September 2009 through December 2010 and at the Sugar Creek, Kentucky, test site (EOR III) from May 2009 through May 2010. A total of 6,950 tons (6,300 tonnes) of CO_2 were injected at the Mumford Hills site, and a total of 7,230 tons (6,560 tonnes) of CO_2 were injected at the Sugar Creek site. The CO_2 storage and injection equipment performance, design capacity, and lessons learned for both sites are presented and discussed in this report.

Key conclusions and recommendations related to CO_2 injection equipment at the Mumford Hills and Sugar Creek sites are as follows:

1. Equipment used for CO_2 storage, pumping, and heating at these sites was designed and operated to better meet the performance and reliability requirements with less need for operator support and intervention than equipment used for the previous shorter duration MGSC Phase II Loudon “huff ‘n’ puff” (EOR I) and lower volume Tanquary enhanced coal bed methane test sites. The booster pump, main pump, and pressure control system were modified to allow for more reliable operation over the more extended test durations.

2. Delivery routes for CO_2 and related weight limit restrictions on roads in winter weather can affect liquid CO_2 injection tests such as those at the Mumford Hills and Sugar Creek sites. From an equipment perspective, allowing for more on-site storage tank capacity might reduce the impact of the winter weather-related weight limit restrictions.

3. Beyond the equipment normally required for water injection floods in the Illinois Basin, additional equipment required for CO_2 injection includes a booster pump, pressure relief valves, an automated (as opposed to manual) surface pressure control system, a process heater, and alternate seal materials that are suitable for CO_2 service.

4. Operation of CO_2 injection equipment, particularly start-up of the equipment, requires additional operator attention and training beyond that needed for a normal water injection flood.

5. Storage tank reloading operations could have been simplified either by operating the storage tanks at lower pressure by reducing the pressure relief valve set point or by adding refrigeration systems to the CO_2 storage tanks. Delivery personnel frequently had to vent CO_2 from the storage tanks before refilling them in order to lower the pressure in the CO_2 storage tanks.

EXECUTIVE SUMMARY

This report describes the design and performance of the surface equipment used for CO_2 storage and injection during the Midwest Geological Sequestration Consortium (MGSC) Validation Phase (Phase II) enhanced oil recovery (EOR) pilot test at the Mumford Hills, Indiana, test site (EOR II) from September 2009 through December 2010 and at the Sugar Creek, Kentucky, test site (EOR III) from May 2009 through May 2010. A total of 6,950 tons (6,300 tonnes) of CO_2 were injected at the Mumford Hills site, and a total of 7,230 tons (6,560 tonnes) of CO_2 were injected at the Sugar Creek site. The CO_2 storage and injection equipment performance, design capacity, and lessons learned for both sites are presented and discussed in this report.

The equipment described in this report includes the liquid CO_2 storage tanks, booster pump, main triplex pump, automated surface pressure control system, flow meter(s), process (line) heater, and associated piping and instruments that were used for CO_2 injection at the Mumford Hills and Sugar Creek sites. The choice of pumping equipment was based on one to three 20-ton truck deliveries of CO_2 per day at about 300 psi (2.07 MPa) and 0°F (-18°C).

The objectives related to CO_2 injection during the MGSC Mumford Hills and Sugar Creek pilot tests were met using the surface equipment described in this report, but a number of lessons were learned along the way. Key CO_2 storage and injection equipment-related conclusions and recommendations based on operations at the Mumford Hills and Sugar Creek sites are as follows:

1. Equipment used for CO_2 storage, pumping, and heating at these sites was designed and operated to better meet the performance and reliability requirements with less need for operator support and intervention than equipment used for the previous shorter duration MGSC Phase II Loudon “huff ‘n’ puff” (EOR I) and Tanquary enhanced coal bed methane test sites. The booster pump, main pump, and pressure control system were modified to allow for more reliable operation over the more extended test durations.

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Advanced planning is required in initial phases of pilot-scale CO_2 injection tests. Budget and site location dictate requirements for unattended versus attended operation, which influences the design of the injection system. Requirements of injection rate, injection rate turndown (the capability of equipment to run at rates lower than its design capacity), surface pressure, surface pressure limits, and minimum temperature of CO_2 delivered to the injection well; requirements for automated and manual data collection; availability of electricity and other utilities (e.g., propane for the in-line heater, natural gas, water, and compressed [instrument] air); and proximity to other equipment, roads, residences, and businesses will all have a bearing on the design, cost, and operational logistics for the injection equipment.

CONTENTS

INTRODUCTION

The Midwest Geological Sequestration Consortium (MGSC), led by the Illinois State Geological Survey (ISGS), conducted CO_2 storage (also called sequestration) testing of all types, including enhanced oil recovery (EOR), at five different sites in the Illinois Basin. The objectives of the Validation Phase (Phase II) Department of Energy (DOE)/NETL (National Energy Technology Laboratory) Regional Partnership project were to assess the feasibility of CO_2 injection, the CO_2 storage potential, and the potential for enhanced oil or gas recovery associated with injecting CO_2 into different types of formations with variable subsurface properties.

This report addresses the design and performance of the CO_2 surface injection equipment used at the Mumford Hills and Sugar Creek pilot test sites, including the equipment used for CO_2 storage, pumping, and heating. It describes the equipment used for these tests, summarizes its operating performance and design capacity, and reviews the lessons learned from operation of this equipment at these sites. This report does not include process data related to the actual injection, such as the time history of injection rates, temperatures, and pressures. These data have been presented elsewhere (Frailey et al., 2012a, 2012c).

Surface injection equipment at the Mumford Hills and Sugar Creek sites included two liquid CO_2 storage tanks per site, a rotary vane booster pump, a triplex plunger pump, a liquid turbine flow meter, and a propane-fired line heater—along with the necessary valves, instrumentation, and safety equipment.

The booster pumps used at the two sites were identical, as were the main triplex plunger pumps. The propane-fired line heater at the Mumford Hills site was rated for 250,000 Btu/hr (263,800 kJ/hr) and the propane-fired line heater at the Sugar Creek site was rated for 100,000 Btu/hr (105,520 kJ/hr). A return line on the booster pump discharge and a pressure control valve on the discharge side of the main pump at each site allowed the systems to be operated at constant surface pressure injection conditions.

PROCESS DESIGN

The objective of the CO_2 injection pilot tests was to test the feasibility of injecting CO_2 into various formations with different subsurface properties and to assess associated enhanced oil and gas recovery potential attributable to CO_2 injection. The Phase II tests included in the original design basis were characterized as the enhanced coal bed methane (ECBM; Tanquary) test (Frailey et al., 2012b), the EOR I “huff ‘n’ puff” (Loudon) test (MGSC, 2009), the miscible liquid CO_2 flood test (Mumford Hills), the immiscible liquid CO_2 flood test (Sugar Creek), and the deep saline injection test.

The “huff ‘n’ puff” (Loudon) test involved injecting CO_2 into a single producing well; after CO_2 injection, the well was shut in, allowing the CO_2 to diffuse into the oil. The well was then placed back into production and the oil and CO_2 were produced. The miscible liquid CO_2 flood test (Mumford Hills) involved converting an existing producing well to handle CO_2 injection and producing oil from existing surrounding production wells. The immiscible liquid CO_2 flood test (Sugar Creek) was similar except that a converted water injection well was used to inject CO_2.

The original design criteria for the pumping equipment could not be used for several reasons, and the expected reservoir pressures and depths for the final well test sites resulted in higher expected surface pressure requirements than were estimated in the original design criteria for the 2006 MGSC Phase II Project. The CO_2 injection pump skid used in the “huff ‘n’ puff” and ECBM tests was not designed to achieve the expected surface pressures necessary for the Mumford Hills and Sugar Creek test sites, and the goal was to have a pump that was automated without a 24-hour operator. Therefore, alternate surface injection equipment capable of meeting these needs was used at these sites.

Process Description

The pump skids used at the Mumford Hills and Sugar Creek sites were designed to inject CO_2 at surface pressures up to 2,000 psig (14 MPag). A rotary vane booster pump was used to reduce or prevent vapor locking in the triplex plunger pump by increasing the pressure of the feed to the plunger pumps to approximately 25 psi (172 kPa) above the inlet pressure from the storage tank. A triplex plunger pump specifically designed for liquid CO_2 was installed downstream of the booster pump. There was a CO_2 return line to the storage tanks on the discharge lines of both the booster pump and the main triplex pump. The two storage tanks were manifolded together, with vapor and liquid pressure equalization lines connecting the two tanks.

Each pump skid was equipped with a liquid turbine flow meter used to measure the injection flow rate and a transmitter to send a 4- to 20-mA signal proportional to the flow rate to a data recorder. Temperature and pressure indicators were available for manual recording of the triplex pump's suction and discharge temperatures and pressures.

An automated pressure control valve (PCV) was located on the return line of the triplex pump discharge at both sites. The automated PCV at the Mumford Hills site was connected to a pressure transmitter on the outlet of the line heater; at the Sugar Creek site, the pressure transmitter was located upstream of the line heater. The position of the pressure transmitter relative to the line heater was different at the two sites only for ease of installation. If the discharge/injection set pressure was not exceeded, all of the CO_2 flowed into the injection discharge line to the injection well. If the discharge set pressure was exceeded, some of the CO_2 was diverted back to the storage tank through the PCV in order to meet the surface injection pressure set point on the main discharge line.

A propane-fired line heater downstream of the flow meter heated the CO_2 prior to delivery to the injection well. Mechanical temperature and pressure gauges were installed between the line heater and the wellhead so that the temperature and pressure of the CO_2 injected into the wellhead could be manually recorded.

The surface facilities at the Mumford Hills and Sugar Creek sites also provided for automatic measurement and recording of the following parameters:

- Booster pump inlet and outlet temperature and pressure
- Main pump outlet temperature and pressure
- CO_2 injection rate
- Line heater outlet temperature
- Wellhead (surface tubing) temperature and pressure

Typical operations at the converted water injection well (Mumford Hills) pilot test site, as indicated by field temperature, pressure, and flow meter readings, were as follows:

- CO_2 injection rates ranged from 20 to 35 tons/day (18 to 32 tonnes/day, 3.2 to 5.7 gpm [17.4 to 31.1 m^3/day], 111 to 195 bbl/day).
- Typical CO_2 supply conditions to the booster pump inlet were -8 to 0°F (-22 to -18°C) and 250 to 290 psig (1.7 to 2.0 MPag).
- The booster pump raised the pressure by about 25 psig (172 kPag).
- Typical CO_2 discharge conditions from the main (triplex) pump were -6 to 2°F (-21 to -17°C) and 630 to 670 psig (4.3 to 4.6 MPag).
- CO_2 leaving the line heater was heated to about 40°F (4°C).

These values are representative of typical operations and are presented here to provide an understanding of the operational requirements of the CO_2 storage, pumping, and heating equipment during CO_2 injection at this site. Actual data for these parameters have been reported elsewhere by the MGSC (Frailey et al., 2012a).

Typical operations at the new CO_2 injection well (Sugar Creek) pilot test site, as indicated by field temperature, pressure, and flow meter readings, were as follows:

- CO_2 injection rates ranged from 20 to 30 tons/day (18 to 27 tonnes/day, 3.2 to 4.9 gpm [17.4 to 26.7 m^3/day], 111 to 167 bbl/day).

- Typical CO_2 supply conditions to the booster pump inlet were -4 to 2°F (-20 to -17°C) and 270 to 300 psig (1.9 to 2.1 MPag).
- The booster pump raised the pressure by about 25 psig (172 kPag).
- Typical CO_2 discharge conditions from the main (triplex) pump were 6 to 12°F (-14 to -11°C) and 1,270 to 1,310 psig (8.75 to 9.025 MPag).
- CO_2 leaving the line heater was heated to about 60°F (16°C).

These values are representative of typical operations and are presented here to provide an understanding of the operational requirements of the CO_2 storage, pumping, and heating equipment during CO_2 injection at this site. The CO_2 at Sugar Creek was heated to a higher temperature because it takes less heat input to increase the temperature of supercritical 1,300-psig (8.964-MPag) CO_2 than it does to heat 600-psig (4.14-MPag) CO_2; heat input is required to first vaporize all 600-psig (4.14-MPag) CO_2 before its temperature rises from further heat input. Actual data for these parameters have been reported elsewhere by the MGSC (Frailey et al., 2012c).

Figure 1 shows an example piping and instrument diagram based on the Mumford Hills test site equipment. However, Figure 1 also shows subsequent design recommendations for the addition of pressure relief valves and does not necessarily represent the exact construction of the unit used in these tests. Figure 2 shows an example piping and instrument diagram based on the Sugar Creek test site equipment. However, Figure 2 also shows subsequent design recommendations for the addition of pressure relief valves and does not necessarily represent the exact construction of the unit used in these tests. Two valves were put in series (PV-100 and PV-101) for manual start-up and automatic normal operations. The manual PV-100 valve was used at start-up and backed all the way out (disabled) for normal operations. Likewise, the equalizing valve (V1) was open prior to and during booster pump start-up so that CO_2 vapor and some associated pressure were downstream of the pump. Otherwise, the liquid CO_2 would flash to dry ice if the downstream pressure was too low when the pump started.

Safety

A number of steps were taken to ensure that the CO_2 injection systems at the two EOR sites were designed and operated in a safe manner. Appendices A and B give an example of the standard operating procedures used for on-site equipment, which, in this case, were the procedures for start-up and shutdown of the line heater and changing the set point on the automated pressure control system. A site-specific Health and Safety Plan (HASP) was developed to document the health and safety risks associated with CO_2 handling and with the operation of CO_2 injection equipment, and to provide site-specific emergency response procedures.

The CO_2 injection equipment was designed and built with several safety features. Full-flow pressure relief valves protected the system from overpressure that could have been caused by a blocked pump discharge. Some additional relief valves were installed so that liquid could not be trapped between valves and overpressure the system because of thermal expansion. When the equipment was operated in automatic mode, interlocks would shut down the entire unit if the booster pump discharge pressure was too high or too low or if the main pump discharge pressure was too high or too low. An interlock is an automatic shutdown that is activated when a problem condition is detected, such as very low main pump discharge pressure, which could indicate a pipeline leak. Ambient CO_2 monitors were also provided and used during the testing to alert operations personnel of any potential leak or release of CO_2.

CO_2 STORAGE AND PUMPING EQUIPMENT

The Mumford Hills and Sugar Creek pilot injection systems included two storage tanks per site, a booster pump, a triplex plunger pump, a liquid turbine flow meter, an automated pressure control system, and a propane-fired line heater—along with the necessary valves, instrumentation, and safety equipment. Further details on the instrumentation and data acquisition can be found in the full reports (Frailey et al., 2012a, 2012c).

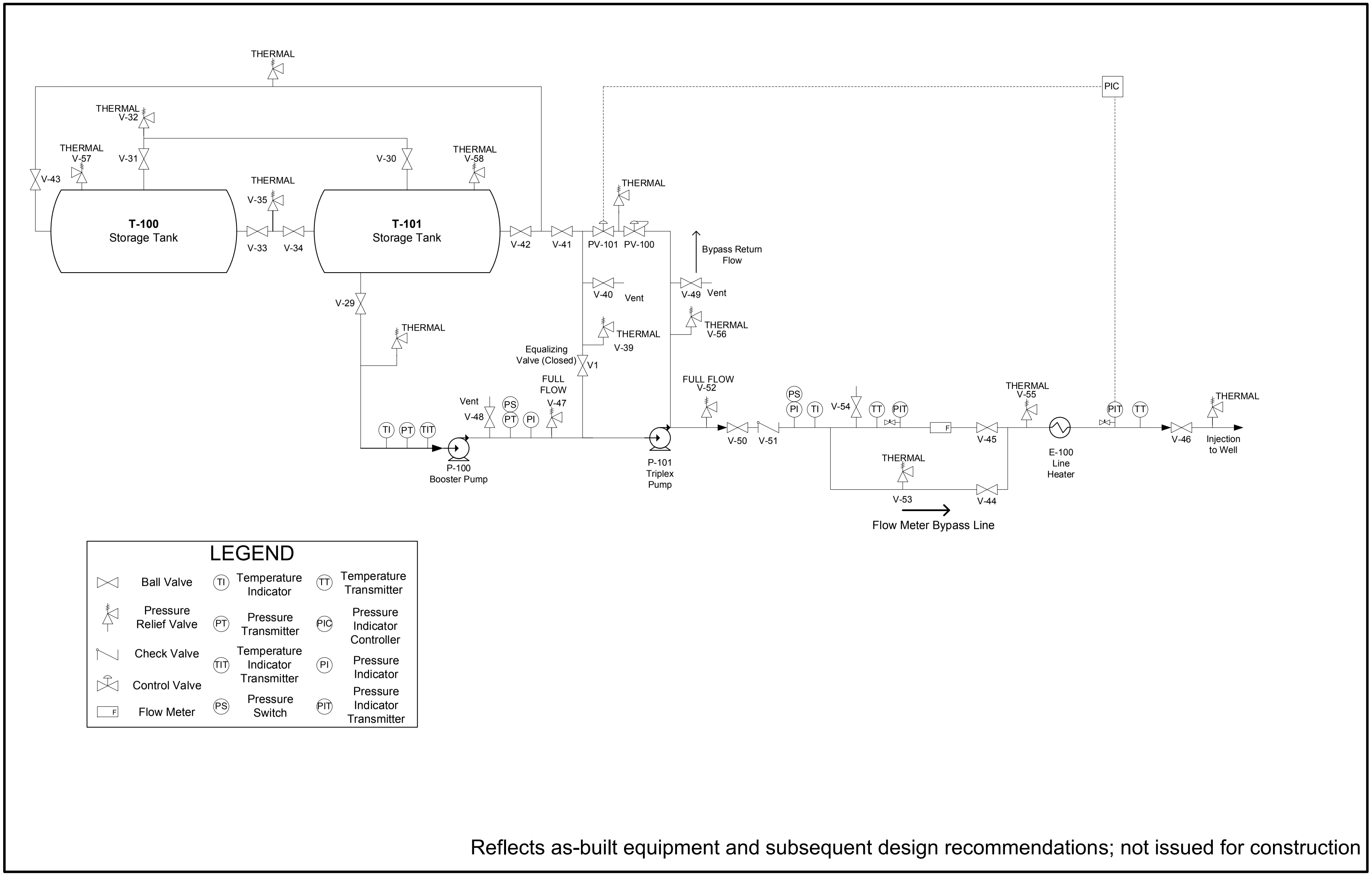
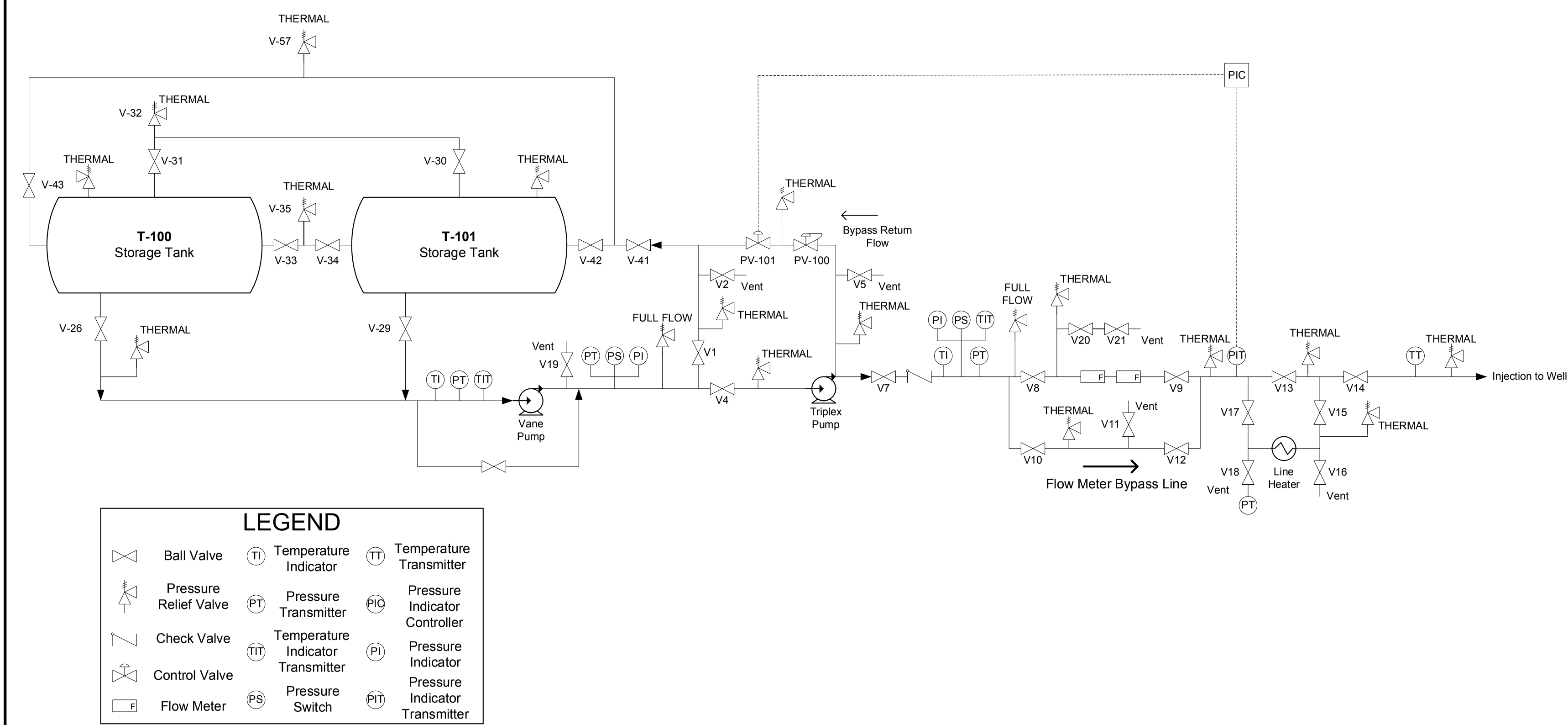


Figure 1 CO_2 injection pump skid piping and instrument diagram—Mumford Hills (EOR II).



Reflects as-built equipment and subsequent design recommendations; not issued for construction

Figure 2 CO_2 injection pump skid piping and instrument diagram—Sugar Creek (EOR III).

CO_2 Storage Tanks

At the Mumford Hills site, CO_2 was stored on-site in two 60-ton (54-tonne) insulated, nonrefrigerated storage tanks leased from Air Liquide. One of these two tanks was also used for the Tanquary pilot. (Injection rates at Tanquary did not merit the use of a second tank.) At the Sugar Creek site, the CO_2 was stored on-site in two insulated, nonrefrigerated 50-ton (45-tonne) storage tanks leased from Praxair. One tank served as the primary feed tank at each site, whereas the second storage tank held a reserve supply in case CO_2 delivery problems arose.

Figures 3 and 4 show the Mumford Hills storage tanks and their connections. Each storage tank was approximately 49 ft (14.9 m) long, 8 ft (2.4 m) in diameter, and 13 ft (4.0 m) high and weighed 60,000 lb (27,000 kg) when empty. Each tank used two 4-in. (10-cm) liquid CO_2 connections and three 2-in. (5-cm) vapor CO_2 connections. The storage tanks at Sugar Creek were approximately 45 ft (14 m) long, 8 ft (2.4 m) in diameter, and 13 ft (4.0 m) high and weighed 45,000 lb (20,000 kg) when empty. Each tank used two 4-in. (10-cm) liquid CO_2 connections and three 2-in. (5-cm) vapor CO_2 connections.

Figure 3 Two 60-ton (54-tonne) Air Liquide CO_2 storage tanks at the Mumford Hills site. Data acquisition equipment can be seen in the left foreground.

Figure 4 CO_2 storage tank connections at the Mumford Hills site. The frosted-over 4-in. tee going to the black hose is liquid CO_2 supply. The black hose is an insulated line to the booster pump suction.

Booster Pump

Booster pumps were used to improve the reliability of the main triplex plunger pumps by increasing the pressure of the feed to the main pumps to approximately 25 psi (172 kPa) above the bubble point of the liquid. This reduced the possibility of vapor locking of the plunger pumps. The Mumford Hills and Sugar Creek booster pumps, one of which is shown in Figure 5, were model CRL1.25 rotary vane pumps manufactured by Blackmer. The booster pumps were driven by 1-hp motors equipped with 0.75-kW variable-frequency drives (VFD) made by Toshiba. The VFD speed settings were set manually to maintain an approximate 20-psi (138-kPa) differential between the suction and discharge pressures on the booster pumps.

The booster pumps were rated for 13 gpm (71 m^3/day) at a differential pressure of 20 psi (138 kPa), requiring 1.5 hp (1.1 kW) at an impeller speed of 1,150 rpm. The maximum capacity of the booster pumps was approximately 15 gpm (82 m^3/day) at 5 psi (34 kPa) of differential pressure. A 1-hp motor was used instead of the 1.5-hp motor referenced on the pump specification sheet because 1-hp motors are commonly available and were sufficient to do the job.

Figure 5 The booster pump (frosted over) at the Mumford Hills site and the gray 1-hp motor (left foreground). A manual temperature gauge (circular dial) and Siemens pressure gauge (blue cap) can be seen to the right. The black hose connects to the storage tanks on the right and to the main pump on the left.

Main CO_2 Triplex Plunger Pump

The main CO_2 pump at each site was a Model 3521 triplex plunger pump manufactured and supplied by CAT Pumps and driven by a 15-hp motor equipped with an 11-kW VFD made by Toshiba. The VFD speed settings were manually adjusted to achieve the desired CO_2 injection rate. The triplex plunger pump itself was capable of delivering liquid CO_2 at 23 gpm (125 m^3/day) and discharge pressures up to 2,000 psi (13.8 MPa) with a power requirement of 31.6 hp (23.6 kW). A 15-hp motor was used instead of the higher horsepower requirements referenced on the pump specification sheet because 15-hp motors are commonly available and were sufficient to do the job. Figures 6 to 8 show pictures of the skid at the Mumford Hills pilot, the CAT pump, and the pump control panel, respectively.

Figure 6 The booster pump skid at the Mumford Hills site. The pump (frosted over) is in the center of the picture and the motor is the gray object behind it. The pipes are covered with black neoprene pipe insulation; the one on the left extends back to a storage tank.

Figure 7 The CAT pump with input and output lines (frosted over) in operation at the Mumford Hills site. The aluminum housing covers the belt and pulleys between the pump and crankcase (blue) and motor (gray).

Figure 8 The pump control panel at the Mumford Hills site.

Liquid CO_2 Turbine Flow Meter

At both the Mumford Hills and Sugar Creek sites, a Cameron NuFlo 0.5-in. (1.3-cm) liquid turbine flow meter was installed to measure the CO_2 injection rate. This flow meter can accurately measure between 0.75 and 7.5 gpm (4 and 41 m^3/day, 25 and 256 bbl/day) of liquid CO_2 according to the equipment specifications provided by the supplier. This particular type of flow meter is a volumetric measuring turbine type; the flowing CO_2 fluid engages the vaned rotor, causing it to rotate at an angular velocity that is proportional to the fluid flow rate. The angular velocity of the rotor results in the generation of an electrical signal (AC sine wave type) in the pickup. The summation of the pulsing electrical signal is directly related to the total flow. The frequency of the signal relates directly to the flow rate.

At the Sugar Creek site, a Sierra Vortex Meter Model 240-VTP-H2-E2-DD-PV1-V6M-ST-MP5 was installed to provide an additional flow measurement option. This InnovaMass Model 240 in-line mass vortex flow meter measures the liquid CO_2 velocity, temperature, and pressure and calculates mass flow rate, volumetric flow rate, and density in a single integrated meter with a digital display. The 0.5-in. (1.3-cm) flow meter used had a 12- to 36-VDC input power source and three 4- to 20-mA analog outputs. It was capable of measuring CO_2 flow rates of 0.9 to 22 gpm (4.9 to 120 m^3/day, 31 to 753 bbl/day) at temperatures between –40 and 500°F (–40 and 260°C) and at pressures up to 1,500 psi (10.3 MPa), according to the equipment specifications provided by the supplier. Figure 9 is a picture of the turbine flow meter in operation at the Mumford Hills site, and Figure 10 shows the two flow meters installed in series at the Sugar Creek site.

Figure 9 The NuFlo turbine flow meter at the Mumford Hills site. The in-line heater can be seen in the background on the left. The frost-covered pipe extending to the right is the pump discharge line.

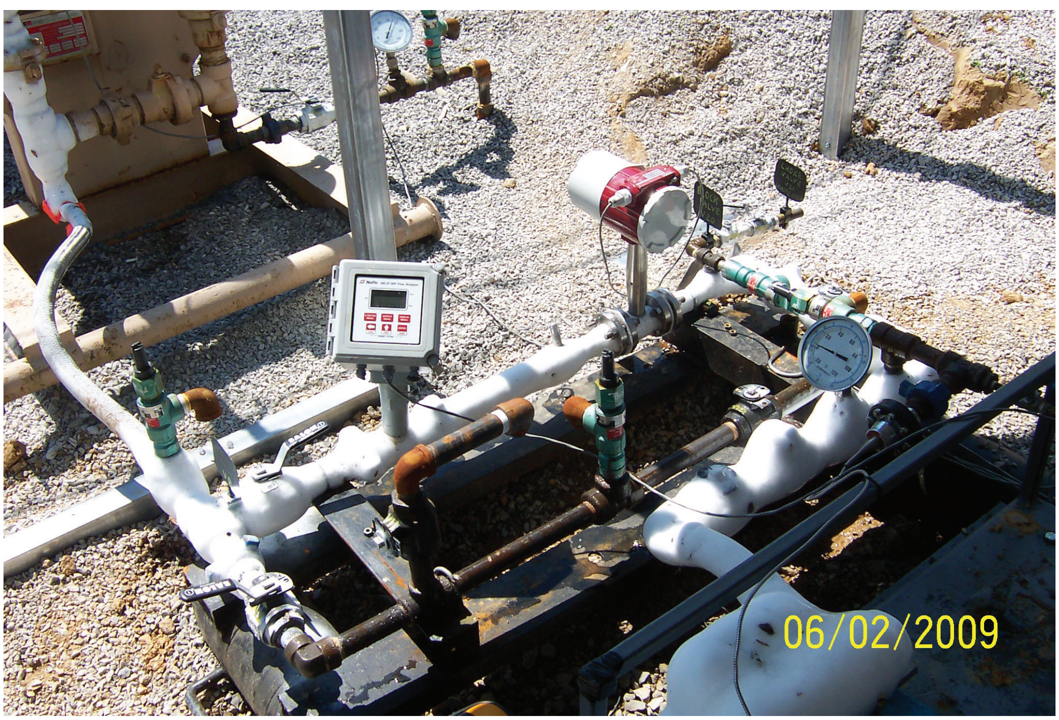


Figure 10 Two flow meters in series at the Sugar Creek site. The white pipe on the left is connected to the in-line heater.

Automated Pressure Control System

The automatic pressure control systems at both injection sites were designed to recycle CO_2 back to the storage tanks in order to maintain a constant discharge pressure in the injection line going to the injection well. A pressure transmitter measured the pressure of the CO_2 in the line going to the injection well and sent a signal to the controller that adjusted the amount of CO_2 recycled by the pressure control valve back to the storage tank to maintain the pressure set point in the injection line. At the Mumford Hills site, the pressure transmitter was located on the outlet of the line heater. At Sugar Creek, the pressure transmitter was installed on the CO_2 inlet to the line heater. The differing locations of the pressure transmitters relative to the line heater at the two sites were made only for ease of installation. Placing the transmitter near the line heater separated the transmitter from vibrations from the pump skid.

The pressure control valve, shown in Figure 11, is a 1-in. (2.5-cm) Type 1711 Globe Cast Control Valve manufactured by BadgerMeter Inc. The valve has an EVA-200 electric actuator, a 4- to 20-mA input signal, and linear size "G" trim with a flow coefficient of 0.2. In case of a loss of signal, the control valve fails in the open position; if the site loses power, then the valve remains in its position prior to the loss of power. The pressure transmitter that signals the pressure control valve, shown in Figure 12, is a Siemens Model Sitrans P 7MF4033-1EA10-1AC1-Z with flush-mounted process connections.

The Model CNi3253-C24 Omega Controller, shown in Figure 13, compares the actual pressure relayed from the pressure transmitter to the pressure set point and provides an output to the pressure control valve.

Figure 11 The pressure control valve at the Mumford Hills site. Identical automated pressure control systems were used for the Mumford Hills and Sugar Creek sites.

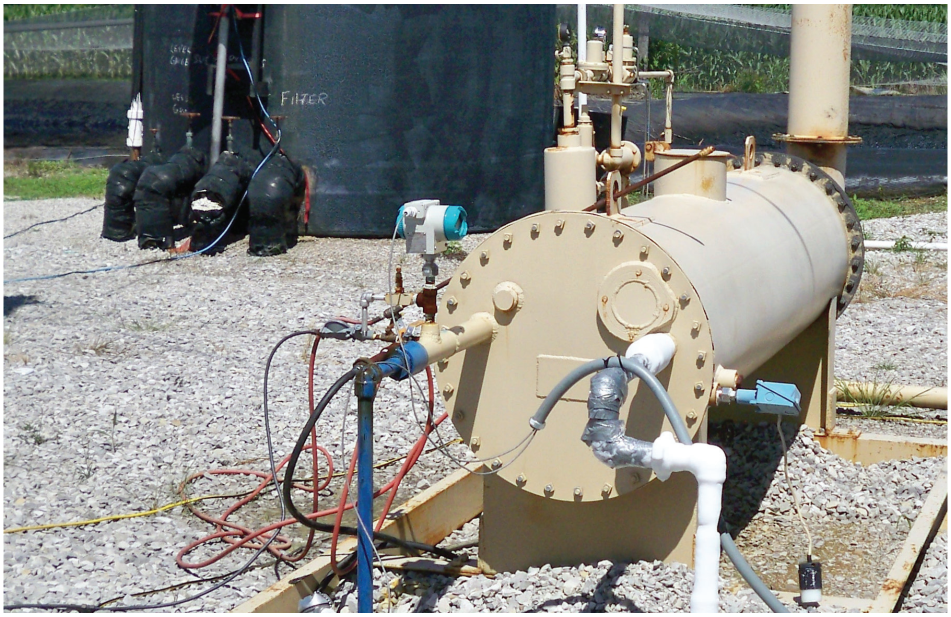


Figure 12 The pressure transmitter at the Mumford Hills site located on the in-line heater. The transmitter is the blue and white object attached vertically to the CO_2 discharge line.

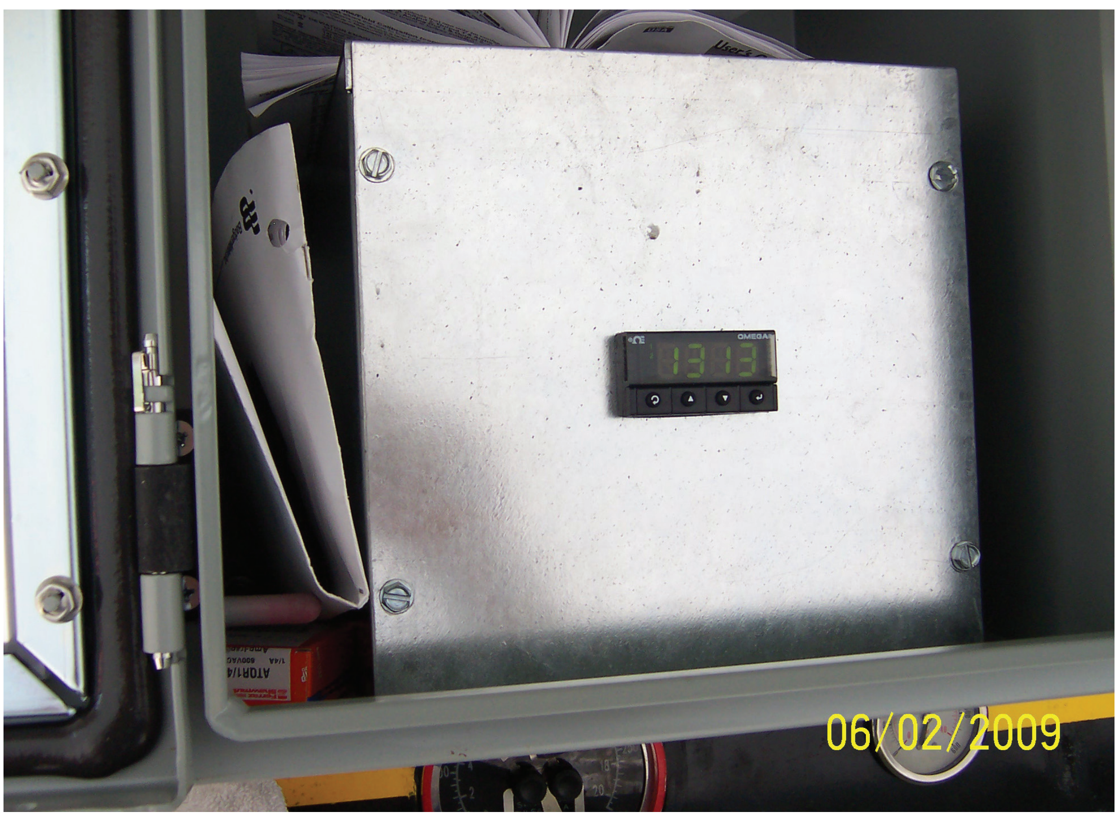


Figure 13 The pressure controller at the Sugar Creek site. Identical systems were used for the Sugar Creek and Mumford Hills sites.

Propane-Fired Line Heater

At the Mumford Hills and Sugar Creek sites, the liquid CO_2 discharged from the flow meter passed through a line heater supplied by Natco. Figure 14 shows a picture of the reconditioned line heater at Mumford Hills, and Figure 15 shows the line heater at Sugar Creek. Table 1 gives a summary of the specifications for line heaters at each test site. Schedule 80 tubing was configured into the horizontal tube passes for each heat exchanger coil, with 180-degree elbows connecting each pass. The heaters were equipped with a standard fuel gas manifold with a thermostat, a thermometer, regulators, and a fuel gas drip scrubber. A skid and lifting lugs were added to the heaters for increased portability.

Table 1 Summary of specifications for the line heaters located at the Mumford Hills and Sugar Creek sites

Test site	Capacity	Diameter	Length	Heat exchanger coil
Mumford Hills	250,00 Btu/hr (263,800 kJ/hr)	2 ft (0.6 m)	8 ft (2.4 m)	8 horizontal passes; 2 in. (5 cm) in diameter; 7 ft (2.1 m) long
Sugar Creek	100,000 Btu/hr (105,520 kJ/hr)	2 ft (0.6 m)	10 ft (3 m)	4 horizontal passes; 2 in. (5 cm) in diameter; 9 ft (2.7 m) long

The shell side of each line heater was partially filled with a 50/50 (volume per volume) mixture of propylene glycol and water. Propane fuel gas was burned in a burner that discharged hot flue gas into a horizontal U-shaped fire tube immersed in the lower portion of the glycol mixture. Heat released by the burning fuel gas was transmitted through the fire tube wall to the glycol mixture. The desired propylene glycol/water bath temperature was maintained within upper and lower dead band limits by turning on and off the fuel gas flow to the burner, based on thermostatic control of the solution temperature. The CO_2 passed through the flow coil of the heater, which was immersed in the upper portion of the solution. Heat was transmitted from the propylene glycol/water solution through the tube wall to the CO_2 inside the flow coil.

Figure 14 The 250,000-Btu/hr (263,800-kJ/hr) line heater at the Mumford Hills site. The main pump skid and storage tank can be seen on the right.

Figure 15 The 100,000-Btu/hr (105,520-kJ/hr) line heater at the Sugar Creek site. The frosted-over line is the inlet to the heater. The outlet from the heater (lower right) leads to the CO_2 injection line.

Ambient CO_2 Monitors

A Telaire 7000 ambient CO_2 monitor enclosed in a customized enclosure was used to measure ambient CO_2 concentrations at each injection site and was calibrated as a function of temperature. The monitor had a range of 0 to 10,000 ppmv ± 50 ppmv and 32 to 122°F (0 to 50°C). Figure 16 is a picture of one of the ambient CO_2 monitor system instruments with a red light beacon and high-audible alarm (gray box below red light).

Figure 16 Ambient CO_2 monitor at the Tanquary site with the equipment trailer in the background.

If ambient CO_2 concentrations exceeded 2,000 ppmv, then an audible alarm and light beacon (both supplied by Lab Safety Supply and manufactured by Federal Signal Corporation) would be activated. Most CO_2 leaks would also be seen and/or heard directly if they occurred. The ambient CO_2 monitors were an additional safeguard against leaks that could occur unnoticed and result in an accumulation of CO_2 in the atmosphere near the pilot test site.

LESSONS LEARNED FROM INJECTION OPERATIONS

The Mumford Hills and Sugar Creek injection systems were designed to maintain consistent surface injection pressure without continous and direct operator attention. However, a number of lessons were learned during the Mumford Hills and Sugar Creek injection tests.

Start-up Issues

Problems with piping insulation, booster pump speed settings, and line packing downstream of the pump skids during start-up of the system were noted at the Mumford Hills site. Insulation was added to the piping on the Mumford Hills and Sugar Creek pump skids during start-up and was subsequently left in place after start-up. To prevent the pumps from losing their prime (vapor locking) during start-up, liquid CO_2 had to be pumped through the booster pump and the triplex pump and then vented to atmosphere to cool down the pumps before the start of injection operations. Prior to beginning injection, approximately 300 to 400 psig (2.1 to 2.8 MPag) of CO_2 vapor was needed downstream of the triplex pump to avoid vapor locking and potential damage to the pump and injection skid.

Moisture in CO_2 Monitor

At the Mumford Hills site, water seeped inside one of the ambient CO_2 monitors because of improper storage between injection tests. The units need to be stored to prevent their internal compartments from becoming covered with liquid water. The Omega controller and the Telaire CO_2 analyzer had to be replaced to restore proper operation of the ambient CO_2 monitor.

Line Heater Detonation

At the Sugar Creek site, soot and smoke emerged from the Natco line heater upon introduction of fuel gas at start-up. The soot and smoke were preceded by a loud boom, which was the result of an improper air-to-fuel ratio in the pilot burner. The issue was resolved by adjusting the air valve (open 3 to 4 turns) and gas valve (open 1 to 1.5 turns) to achieve the proper air-to-fuel ratio.

Injection Line Leaks

The Sugar Creek site was shut down for almost one month because of two injection flow line leaks. Site personnel discovered the first leak on June 30, 2009, by direct observation and stopped injection of CO_2. There was no danger to equipment and no risk to personnel near the injection well. A faulty connection between pipe joints in the injection line was determined to be the cause of the leak. Further details on this have been reported and addressed elsewhere by the MGSC (Frailey et al., 2012c). A second leak occurred in the winter of 2009–2010. During restart of injection after the second leak, plugging in the injection line was thought to be due to the formation of H_2O-CO_2 hydrates at temperatures on the order of 38°F (3°C) in the injection line. Water may have seeped into the injection line while it was down for repair. Additional purging and heating of the line using dry, heated CO_2 was required to clear the injection line.

Weather Delays

Winter weather caused interruptions of CO_2 delivery to both EOR sites because CO_2 delivery trucks were unable to reach the sites. Winter road restrictions resulted in 4 months of interruption of CO_2 injection at the Mumford Hills site. After each freeze-thaw cycle, winter road restrictions resulted in a road posting that prohibited driving heavy trucks on some roads. Snow pack and ice on roads leading to the Sugar Creek site interrupted delivery for approximately 10 days.

CO_2 Storage Tank Loading Operations

Operating the storage tanks at lower pressure by reducing the pressure relief valve set point or by adding refrigeration systems to the CO_2 storage tanks would have simplified storage tank reloading operations by maintaining lower operating pressure in the storage tanks. Delivery personnel frequently had to vent some CO_2 from the storage tanks before filling them in order to lower the pressure of the CO_2 in the storage tanks prior to reloading. It is recommended that pilots with several months of injection have refrigeration systems. However, this will increase the lease cost for a tank, require an additional power source, and may not be readily available for rent.

COMPARISON OF CO_2 INJECTION AND WATER INJECTION EQUIPMENT

Typical waterflood equipment in the Illinois Basin is simpler to operate and requires less equipment compared with CO_2 equipment for CO_2 injection. Waterflood operations require a triplex pump, a flow meter, and pressure control on the bypass line back to the water storage tank. However, the pressure control is typically a manual valve as opposed to an automated pressure control system. Triplex pumps can be used in both water and liquid CO_2 pumping services. However, the materials of construction may be different in the CO_2 pumps due to the low temperatures associated with liquid CO_2 pumping and the potential corrosion concerns if the CO_2 pump comes in contact with water. The materials used for seals may also be different for triplex pumps in CO_2 service.

Waterflood operations do not require a booster pump because there is no concern with vapor locking the pumps. They also do not require a line heater because water is stored at temperatures suitable for injection, or pressure relief valves because water does not expand to the degree that CO_2 does when blocked in under pressure, heated from the surroundings, or both.

Start-up of the CO_2 injection equipment was slightly more complex than start-up of the waterflood injection equipment. After start-up, however, the operation of the CO_2 injection and waterflood injection equipment is similar. Additional training was necessary to increase operator familiarity with the CO_2 injection equipment.

CONCLUSION

The equipment used at the test sites met the objectives related to CO_2 injection and provided lessons for future pilot-scale projects, especially systems designed to have a consistent surface injection pressure and less direct operator attention. Waterflood equipment in the Illinois Basin typically has a manual surface pressure control system; therefore, it is necessary to add an automated one, along with an additional booster pump, pressure relief valves, an in-line heater, and alternate seal materials for CO_2 injection. This additional equipment upgrades the existing injection system for more reliable and long-term CO_2 test durations. Moreover, pilots with several months of planned injection should use refrigerated storage tanks to reduce the need for manual venting of CO_2 before refilling the storage tank, which achieves the goal of a more automated system. Refrigeration units are readily available and cost on the order of \$30,000 to \$50,000; power usage is a function of ambient conditions and loading operations and might range from 5 to 30 kW.

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APPENDIX A

Standard Operating Procedures for the Line Heater

LINE HEATER START-UP

- Close all three valves on line heater
- Open propane tank and regulate to 20 psi
- Open 2-in. access to burner
- Insert a WD-40- or gas-soaked cloth into the 2-in. access using a metal rod
- Open small valve to pilot (you should hear it light)
- Remove metal rod from access
- Replace 2-in. cover on burner
- Open bigger valve to main burner

LINE HEATER SHUTDOWN

- Close all three valves on line heater

APPENDIX B

Standard Operating Procedure for the Automated Pressure Control System

TO CHANGE SET POINT FOR ELECTRIC BYPASS VALVE

	DISPLAY SHOULD READ
• Hit ↩	SP1
• Hit ↵	SET POINT IS DISPLAYED (e.g., 1320)
• Change press with ▲ up or ▼ down arrows*	
• Hit ↵ to save set point	SP2
• Hit ↩	CNFG
• Hit ↩	Run, then press gauge reading

*Set point is about 20 psi below desired pressure (makes valve run smoother).